PROPOSED FACILITY MODIFICATIONS TO SUPPORT PROPULSION SYSTEMS TESTING UNDER SIMULATED SPACE CONDITIONS AT PLUM BROOK STATION'S SPACECRAFT PROPULSION RESEARCH FACILITY (B-2)

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ABSTRACT

Preparing NASA's Plum Brook Station's Spacecraft Propulsion Research Facility (B-2) to support NASA's new generation of launch vehicles has raised many challenges for B-2's support staff. The facility provides a unique capability to test chemical propulsion systems/vehicles while simulating space thermal and vacuum environments. Designed and constructed 4 decades ago to support upper stage cryogenic engine/vehicle system development, the Plum Brook Station B-2 facility will require modifications to support the larger, more powerful, and more advanced engine systems for the next generation of vehicles leaving earth's orbit. Engine design improvements over the years have included large area expansion ratio nozzles, greater combustion chamber pressures, and advanced materials. Consequently, it has become necessary to determine what facility changes are required and how the facility can be adapted to support varying customers and their specific test needs. Instrumental in this task is understanding the present facility capabilities and identifying what reasonable changes can be implemented. A variety of approaches and analytical tools are being employed to gain this understanding. This paper discusses some of the challenges in applying these tools to this project and expected facility configuration to support the varying customer needs.

INTRODUCTION

NASA's Plum Brook Station's Spacecraft Propulsion Research Facility (B-2) is a unique facility combining space thermal-vacuum simulation with the ability to 'hot-fire' a rocket engine. This combination yields a highly desired capability to qualify and certify upper stage engine system ignition and restart under space conditions. Historically utilized in the development of the LOX/LH2 Centaur upper stage [using two RL-10, 67 kN (15,000 lbf) engines], the B-2 is now being considered for application to the next generation of space systems involving engine ignition and operations at higher thrust levels while in and beyond earth orbit. For the purpose this paper, only hydrogen-oxygen engines are being addressed.

DESCRIPTION OF EXISTING FACILITY

Constructed in the 1960s, primarily to support the Centaur upper stage development, the Spacecraft Propulsion Research Facility (B-2) provides the facilities to simulate a space thermal soak and subsequent altitude firing of the propulsion system. Testing can consist of a variety of combinations including engine only, engine plus propellant delivery systems, or an integrated stage incorporating tanks and avionics. The facility is equipped with propellant delivery systems for LOX and LH2 plus helium and nitrogen supporting systems and is sized for hydrogen-oxygen engines up to 445 kN (100,000 lbf) thrust and approximately 200 kN (45,000 lbf) thrust for storable (non-condensable) propellant combinations.

Space simulation is accomplished in a stainless steel cylindrical vacuum chamber 11.6 meter (38 feet) diameter with a 18.9 meters (62 feet) vertical height. Vacuum pumping includes 3 stages of mechanical pumps and ten diffusion pumps ultimately bringing the vacuum chamber to a 10^{-4} Pa (10^{-5} Pa with liquid nitrogen in the cold wall) environment for well sealed systems. Thermal simulation is provided on the cold end by a liquid nitrogen cold wall and on the high end by portable lamps configured as required for the test[2].

Engine firing is accomplished by opening an 3.4 meter (11 ft) diameter valve [located at the end of the 12 meter (39 ft) diffuser] allowing the exhaust products to enter a spray chamber which cools and condenses the exhaust through circulation of 848 kL/min (224,000 gpm) of chilled spray water from the water stored in the spray chamber. The 20.4 meter (67 ft) diameter by 36 meter (118 ft) deep concrete spray chamber is pumped by a steam ejector system to transport the remaining exhaust products to the atmosphere.

The steam ejector system consists of two trains each containing three stages. There are intercondensers located between the stages. The ejectors can be run with one, two, or all three stages operating depending upon the desired spray chamber operating pressure and the amount of pumping capacity required.

This paper addresses some of the efforts that have been expended in identifying capabilities and potential modifications of the B-2 exhaust system downstream of the test chamber. The exhaust system includes the following major hardware (see Figure 1 for a location overview):

- Diffuser (engine exhaust duct)
- Vacuum Isolation Valve
- Spray Chamber containing the Condensing Spray System
- Exhaust Piping
- Steam Ejectors (steam generating & supply system not shown)
- Intercondensers

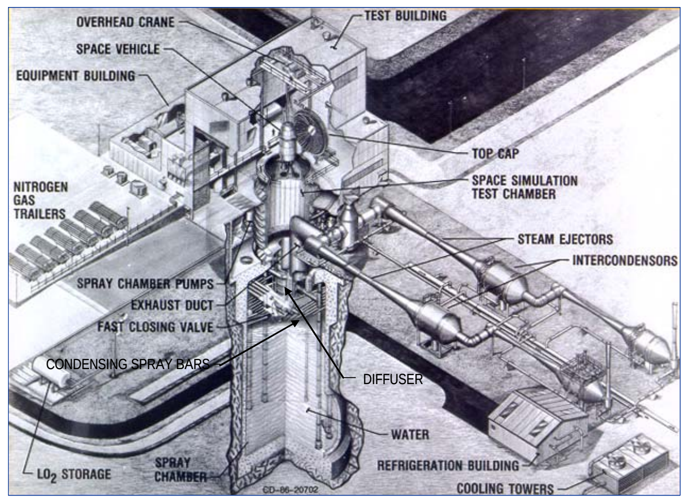

FIGURE 1: B-2 Cutaway

SIGNIFICANT DESIGN/OPERATING ISSUES

Before discussing the detailed analytical aspects, it would be useful to address the two most significant challenges faced in the design modeling efforts. These have specific implications to B-2 and potential engine testing programs:

1. Backflow effects at engine shutdown
2. Condensing spray effectiveness.

Since resolution of these topics will drive the major design modifications required for the exhaust systems, a discussion is included in the following paragraphs.

BACKFLOW EFFECTS AT ENGINE SHUTDOWN

It has been recognized that the current operating mode of the existing diffuser can no longer be utilized with nozzle extensions of large area ratio engines. Since operating diffusers create a pressure difference (the test chamber will be at substantially lower pressure than the spray chamber), a pressure imbalance occurs at the moment of engine shutdown.

The existing exhaust diffuser is a constant area duct opening into the spray chamber. Its only mechanism to prevent backflow of large quantities of exhaust gases and water at the moment of engine shutdown would be to operate the large diameter valve in a fast acting mode. However the fast acting mode is not operational and concerns have been expressed in trying to operate such a large valve in a manner fast enough during a test. Consequently at the time of shutdown, a pressure wave comes back up the exhaust diffuser entraining water and impacting the test article potentially causing damage to fragile nozzle extensions and any nearby unprotected hardware (such as thermal blankets and test instrumentation) as well as adding heat to cryogenic tanks[3]. Water that has splashed inside the test chamber will also create a major problem in trying to pump the test chamber back down to space conditions for test programs running multiple engine firings in space simulation conditions.

As a result, a diffuser concept incorporating a method to prevent backflow is a critical requirement for any future large scale engine testing. Incorporating this requirement will require replacing the existing diffuser with a concept to effectively deal with emergency and unexpected engine shutdowns. A technique being explored to provide this "soft shutdown" capability is the addition of a "steam blocker" in the diffuser design. In this concept, the steam blocker would be active at all times during the test with its function being to prevent the back pressure wave from propagating up the diffuser during engine shutdowns. (See Figure 2)

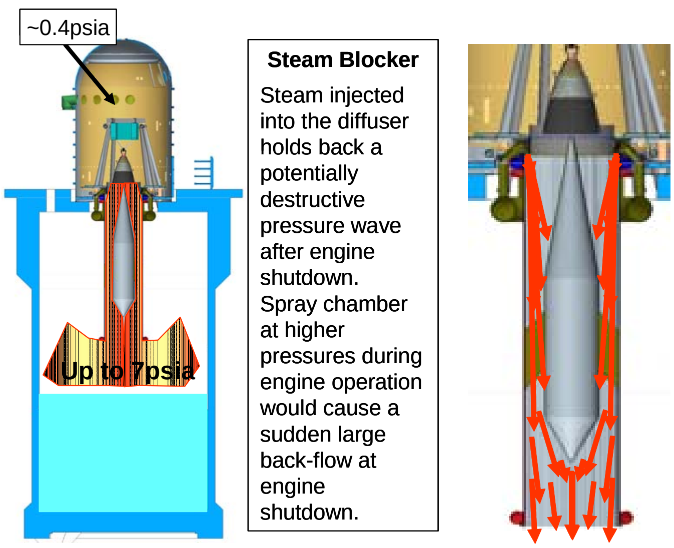

FIGURE 2: Center-Body Diffuser with Steam Blocker

Steam was selected based on two factors: it is readily available from the on-site steam generating capability and it can be condensed by the spray system in the spray chamber (reducing the load on the ejectors). While this method causes significant increases in steam utilization and storage capacity, protecting an expensive engine from damage would more than offset this investment.

Another diffuser design factor is the need to provide an effective altitude simulation for the potentially higher thrust engine testing within the available space at B-2. Performances of diffusers are functions of engine thrust, mass flow, and backpressure characteristics. For B-2 this means modifying the facility to have custom designed interchangeable center body diffusers, a substantial change from the existing B-2 system which utilizes a fixed constant area diffuser. Higher thrust levels would have resulted in constant area diffusers which were too long. It was decided, then, to proceed with a center body diffuser design concept (see Figure 2). This concept has been successfully employed at other facilities both domestic and foreign for several decades. For this study, a preliminary diffuser design is being considered for a 1334 kN (300,000 lbf) thrust class propulsion system.

CONDENSING SPRAY EFFECTIVENESS

Another design challenge to be addressed to meet future engine test requirements is determining the performance of the condensing system. This is a challenge because of the much higher engine thrust classes being considered, 10 times the thrust level of any previous test conducted in B-2. Concern is that the spray bar systems may be inadequate for these higher class engines.

Exhaust system performance is heavily tied to the condensing spray system located in the spray chamber. Water is stored in the spray chamber basin, chilled to lower spray chamber pressure, and circulated through a spray bar distribution system to evenly distribute the water over the spray chamber cross section where it is pumped through nozzles and free falls back to the basin. Its function is to cool and condense the exhaust gases so that exit gas is mostly noncondensable gases. This is an issue because exhaust system operating data is scarce and non existent for thrust levels above 133 kN (30,000 lbf), making prediction of condensing performance very subjective. The present system was designed to maintain a 11.5 kPa (1.67 psia) spray chamber pressure for a LOX/LH2 engine operating at about 445 kN (100,000 lbf) thrust. Resources are not available to support operating the facility to gather specific test data. Thus analytical modeling has become the method of choice.

When looking for appropriate analytical models, it appears most would not accurately represent the B-2 configuration and have generally made assumptions on efficiencies. Tackling the complex fluid flow and gas mixtures problem is not an easy task. Consequently, a model that predicts performance of the spray condensing system over a wide range of conditions and with confidence needs to be developed.

B-2 EXHAUST SYSTEM MODELING

To help answer the questions about facility exhaust system performance for engines operating at conditions beyond B-2 experience, it was deemed necessary to develop an analytical model of the exhaust system.

The initial effort was centered on constructing a simple 1-dimensional, steady state math model in Microsoft Excel so that it can be utilized for various potential users. The primary elements of this model are identified in Figure 4.

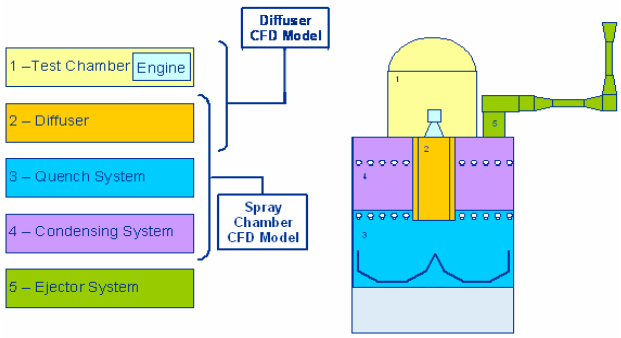

Figure 4: One Dimensional, Steady State Model Functional Elements

Utilizing engine operating parameters at a single point, conservative estimates for the performance of the various elements, and expected ejector pumping capability; it was found that too many assumptions had to be made in the analysis to be comfortable with the outputs. When coupled with a new steam blocker, modeling to predict performance for future facility configurations will be purely a theoretical exercise. As a result a more involved analytical approach has been embraced.

While the analytical efforts are not complete, a description of these efforts and some hints of their products are provided in this paper. The goal remains to develop a simplified 1-D Excel based model. Additional math models are being prepared to address specific system details. Here is a summary of the various efforts:

Full Exhaust System Models:

- 1-D Simplified steady state performance model (condensing efficiency specified)
- 1-D Physics based model (condensing efficiency predicted)

Sub System Models:

- CFD Model of spray chamber
- CFD Model of exhaust diffuser

Experts on Direct Contact Condensation and condensing physics have been brought on-board to improve model fidelity and assist in developing facility modification options.

Keep in mind that potential customers are looking at the possibility of testing engines at thrust levels beyond those identified in the original facility design. Calculations performed by the designers shortly after the original design did look at higher thrust levels and concluded they could be accomplished with some facility modifications and acceptance of lower performance parameters (higher spray chamber pressure).

The exhaust system functional elements (from Figure 4) are examined in more detail in the following paragraphs.

DIFFUSER

Previous sections identified that future engine testing at B-2 should incorporate a soft shutdown capability in a center-body diffuser design. This would be all new hardware at B-2 and consequently there is no available test data to anchor any model. It is necessary to investigate expected performance characteristics based on more in-depth analytical work which can then be summarized and incorporated into the simple model.

A preliminary center-body diffuser concept has been created based upon the historical information used in the development of center body diffusers and through enlistment of one of the original designers. The center-body design offers the best mix of performance within the available spray chamber space.

One of the differences in the B-2 design when compared to other center-body diffusers is the incorporation of the steam blocker upstream of the diffuser throat. The steam blocker acts as a secondary flow source, similar to having an additional engine operating in parallel with the test article, and there is a desire to explore the affect of this parallel operation. Tools used to explore this effect include NCC and CEA/CFX/SINDA.

Due to the large expansion ratios from the steam blocker nozzle, the flow becomes supersonic and the resulting static pressures create conditions that are outside the property tables contained in the codes. These properties result in freezing conditions (solids) not handled very well in the software. Exit conditions of the diffuser are the desired outputs and one preliminary result is shown in Figure 5. In the figure, it can be seen that diffuser exit velocities are quite high, supersonic in this particular configuration.

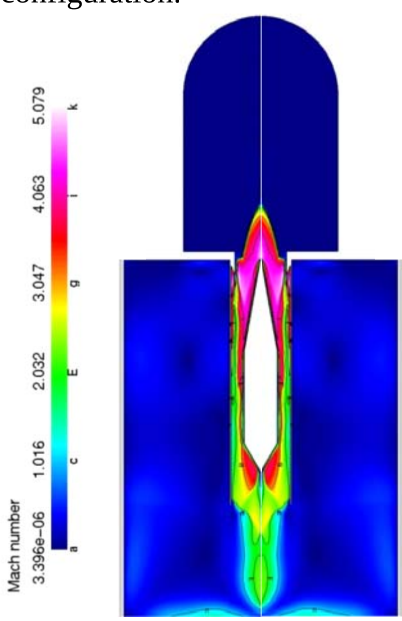

FIGURE 5: One preliminary result showing supersonic exit conditions

Analyses with and without the engine will be performed to explore the steam blocker effect in the diffuser.

Since there is no empirical information on the performance of a steam blocker upstream of a center body nozzle, a cold-flow diffuser scale model test program has been initiated to explore some of the performance sensitivities for various steam injection designs. Also, sensitivity to steam injection location and center-body L/D are part of this testing program. Figure 6 identifies details of the scale model (note – the engine nozzle was not part of this test series).

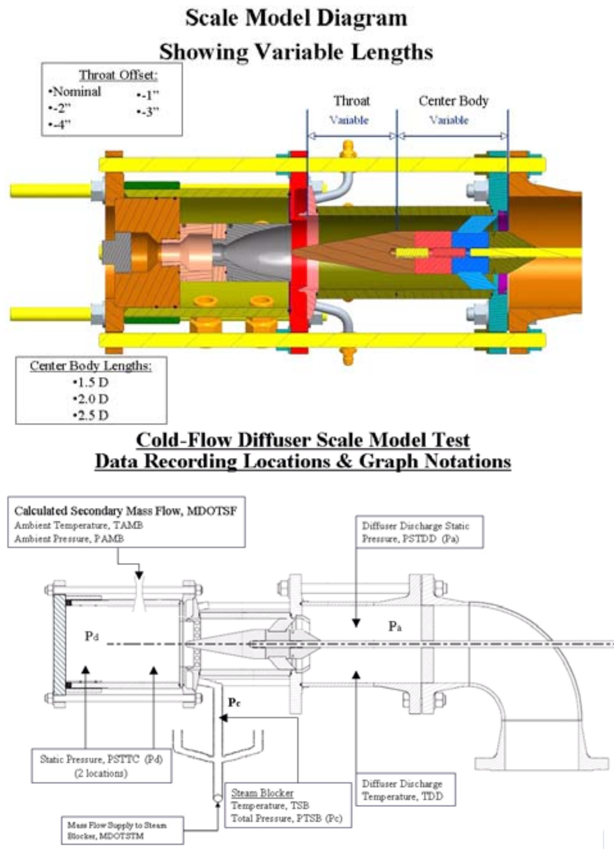

Figure 6: Diffuser Scale Model

QUENCH

While a dedicated quench system is not present in the current spray chamber, the pool of water in the spray chamber is directly impacted by the exhaust stream. This creates a cavity in the pool which at higher thrust levels may require deflectors to be employed. The redirection of the exhaust flow and the turbulent churning at the point of impact contribute to quenching the exhaust flow. Additionally, the backside spray system utilized on the existing diffuser becomes partially entrained in the exhaust gas as it exits the diffuser. A spray system dedicated to the quench process has been considered. While a quantitative evaluation of this contribution to quenching has not been completed, any remaining quench will be accomplished by the condensing sprays in the chamber. At this point, the quench portion of the analysis has not been engaged and is a candidate for future work.

SPRAY CHAMBER CONDENSING SYSTEM

The spray chamber condensing system operates during engine firing to condense out much of the combustion products (steam for LOX/LH2 engines) keeping the spray chamber at a relatively low pressure and reducing the load on the ejectors. The condensing system utilizes chilled water stored in the spray chamber which is then circulated through the spray bar system exposing the subcooled water droplets to the exhaust products. Since little empirical information exists on the performance of the B-2 condensing spray system and none of the data has been obtained at thrust levels even close to the specified maximum design operating point, the project has been relegated to developing an analytical technique to model the condensing system. This is a challenging task as there are many variables and some extreme dynamic interactions taking place.

One of these complicating factors is the presence of un-burned excess hydrogen giving the exhaust stream a multi-species condition and greatly affecting the condensing process. Even small amounts of the non-condensable hydrogen create a significant change in the condensing rates of steam onto the subcooled water drops. Currently, the software codes do not adequately address the presence of the non-condensing hydrogen in the surface condensation on a falling water drop. This effect has been studied through work by Dr. H. R. Jacobs which will lead to implementation of a model to address these concerns.

Another significant challenge in modeling the condensing process is taking into account the distribution of different sized water drops being injected by the condensing sprays. Heat conduction into the water drops is complicated by a “warm” layer of water on the outside of the drop affecting the heat capacity of the drop for the time it is exposed to the spray chamber environment. Coupled with the various drag forces on the different diameter, some drops will fall while others will be entrained and carried aloft.

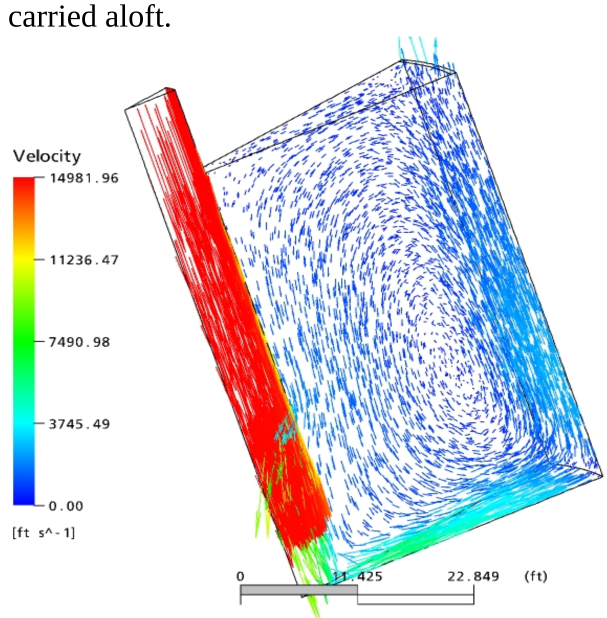

Figure 7: General Model Development, Spray Chamber Slice, Existing Diffuser

Computational and analytical methods are being employed by a few groups to get a better handle on this phenomenon. One of the subsystem models involves a pie shaped wedge of the spray chamber to conduct a CFD analysis for flow conditions using the existing diffuser, see Figure 7. Since some actual test data at lower thrust levels exists, the team is exploring modeling concepts and comparing them against data that is in hand. From the model shown in Figure 7, it should be apparent that the boundary condition associated with the water surface assumed the surface was at a fixed position. One of the highly unknown issues is how the water surface deforms at engine plume impingement, how much turbulence is generated, how much evaporation occurs, and most importantly how to model these effects analytically. Analytical tools employed in this portion of the effort include CEA, CFX, and SINDA.

At the high thrust levels being evaluated, the existing droplet diameters were too small and the liquid flow to the chamber pool was not assured. This necessitated the tracking of the droplets in the analysis. Another challenging aspect was the modeling of the condensing heat transfer process itself with these particles undergoing un-steady flow. Modeling this was difficult and is still an on-going process. This has resulted in the consideration of a structured packing arrangement for the condensing process. Showing success in counter flow condensing processes in the power industry, applying this concept to B-2 is being evaluated and is explained in more detail below. Finally the exhaust gas flow rates can be so large as to cause large cavities to exist in the chamber pool. Design changes to keep the pool flat (added structure) or more complicated analytical modeling due to the cavities will result. This is an on-going process.

Condensing Improvement Options - While understanding the performance of the existing facility is important, it is recognized that the existing spray bar systems may not be sufficient for the larger engines being considered. It is also possible that there are techniques that can increase the condensing effectiveness in the spray chamber. One technique involves the addition of packing inside the spray chamber. Condensation would not then occur on the free falling drops, but on the falling film that results from the spray impinging on the packing material. In B-2 this technique would allow for more efficient utilization of the condensing spray system without increasing the quantity of spray water. In the Figure 8, one can see performance data of condensation of free falling jets versus using packing material in an industrial based system[1]. The figure clearly shows a higher performance level at much lower Jakob numbers. Low Jakob numbers result in reduced required condensing water flow rate.

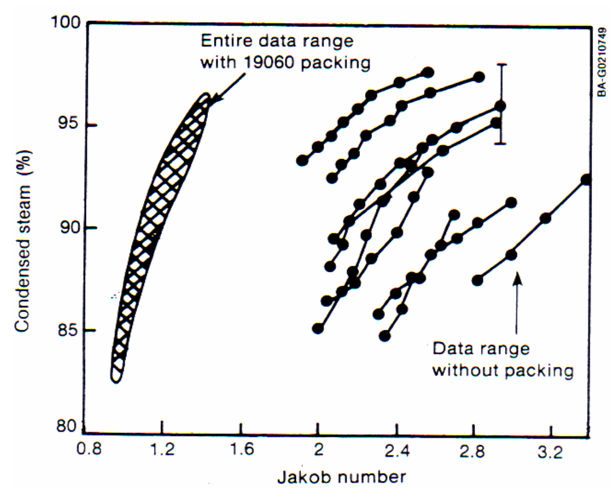

Figure 8: Example Impact of adding Packing

This technique has a promise of allowing higher thrust engines or accommodating the added steam blocker within the existing 848 kL/min (224,000 gpm) condensing spray

flowrate. The evaluation is still underway and when operating at the much higher thrust levels, it may still be necessary to supplement with more cooling water.
At very high thrust levels a stacked arrangement may be used in which the hydraulic diameters of the flow passages decrease as the steam is condensed as one goes up the condenser. One design concern for the structured packing condenser is to design it so that flooding does not occur. Flooding can exist at higher gas flow rates making the liquid bridge the gaps and potentially results in liquid up flow. Some modeling data in Figure 9 shows that a stacked arrangement can be designed to avoid these flooding conditions. The services of NREL have been engaged to assist in this part of the study.

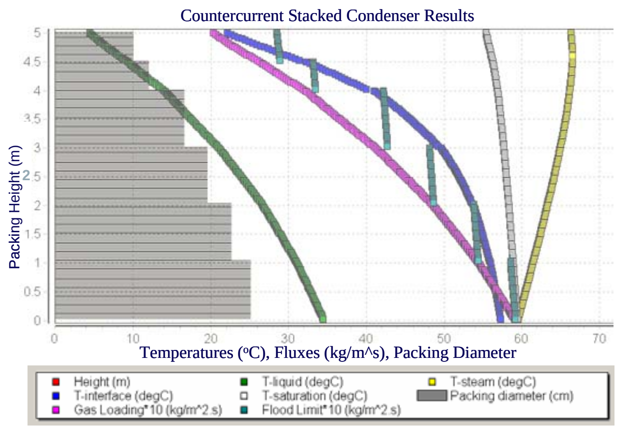

Figure 9: Stacked Packing Impact

EJECTORS

The ejectors in the main exhaust flow path are designed to remove spray chamber gases (water vapor and hydrogen) during operation of the rocket engine at a fast enough rate to maintain a low spray chamber pressure. A couple of changes are being considered for this system.

- For high thrust engines, the existing parallel trains would be augmented by the addition of more trains running in parallel.
- For accommodating the added flowrates imposed by the steam blocker concept, the existing atmospheric stage could be modified to double the current pumping capacity when operating only one stage. The details have not yet been developed.

The intercondensers also serve to help condense the exhaust stream acting as an external condenser when only one or two stages are required. Modeling of this element will be generally through mathematical equations. The difficult part is determining the performance of the existing intercondensers. Again, there is little test data to support any comparison of analytical results to real-life performance. Primary consideration for the ejectors is obtaining actual field measurements of the installed hardware. The general formula for determining ejector performance is well established. The intercondenser performance will ultimately utilize similar techniques as those being employed in the spray chamber.

SUMMARY OF IMPACT ON POTENTIAL FACILITY MODIFICATIONS

The analyses identified in the previous sections of this paper have all been started with the purpose of scoping out exhaust system modifications that may be needed for various engine test programs. A brief summary of the main functions impacted by these analyses is covered in this section.

Applying a brute force approach was not considered appropriate for B-2 as the spray chamber volume configuration is considered too significant a constraint (to expand the spray chamber volume is considered to be not-feasible financially). Due to large implementation costs, this option would have to be carefully determined from a program perspective.

Diffuser - The diffuser operates as a pressure differential device causing altitude test simulation to be a function of spray chamber pressure and the diffuser design. Spray chamber pressure is in-turn a function of ejector pumping capacity, condensing efficiencies in the spray chamber, and pressure drop of the gas flows in through the exhaust system. Design of the diffuser is best optimized for a given engine thrust class, i.e. a diffuser for a large thrust engine would not be the best match for a low thrust engine. Therefore, an interchangeable center-body diffuser would be an appropriate concept to maximize performance while minimizing steam usage for the steam blocker at B-2, and minimizing the required volume needed for the diffuser. Note - Any new diffuser is expected to incorporate a steam blocker capability.

Quench – While there is no current dedicated quench system, it is anticipated that any new diffuser design will incorporate provisions to utilize diffuser cooling water and discharge it into the exhaust stream to perform some of the quench function. Other quench mechanisms could be accomplished by exhaust stream and pool interactions and/or by initial spray system capabilities.

Spray Chamber Condensing System – No one concept is presently favored. Possibilities include an additional spray bar system (essentially doubling the amount of water being sprayed), an addition of packing within the spray chamber allowing the existing water to be more efficiently utilized, or an addition of an external condenser.

Ejectors – In a fairly straight forward way, changes in the ejector configurations entail two types of augmentation. First would be increasing the existing ejectors pumping capacity by modifying the atmospheric stages of each train. Secondly, if needed, additional pumping capacity could be added through the addition of more parallel trains.

SUMMARY

This paper describes some of the technical issues and analytical challenges associated with preparing an established facility to support modern rocket engine propulsion testing. When proposed testing is beyond the limits of previous tests, facility performance guarantees become nebulous and difficult to predict. The Spacecraft Propulsion Research Facility is relying upon analytical modeling and some scale model testing to buildup a level of confidence to support proposed future tests. This is a work in progress with several efforts underway at various levels of maturity.

ACKNOWLEDGEMENTS:

The author would like to thank Myron Hill for providing assistance in review of this paper and specifically for the suggestions leading to the paragraphs relating to packed bed condensers. While this paper is more a high level overview, the efforts of those performing the analytical work must be recognized. Those participating include Barbara Sakowski, Myron Hill, Lauren Clayman, Changju T. Wey, Nan-Suey Liu, Kevin Dickens, Marty Krupar, and Ron Cull from NASA's John H. Glenn Research Center, Dr. Harold R. Jacobs, NREL's Dr. Desikan Bharathan, Reaction Motors Inc.'s Carl Kastner Jr., and CRAFT-Tech Incorporated.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

B-2	NASA’s Plum Brook Station’s Spacecraft Propulsion Research Facility
CEA	Chemical Equilibrium with Applications - CEA is a program which calculates chemical equilibrium product concentrations from any set of reactants and determines thermodynamic and transport properties for the product mixture.
CFX	ANSYS CFX software is a computational fluid dynamics (CFD) technology for simulations of all levels of complexity
gpm	gallons per minute
ft	feet
HTF	Hypersonic Test Facility
kL/min	kiloliter per minute
kN	kiloNewton
kPa	kiloPascals
lbf	pounds force
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
NCC	National Combustion Code - An integrated system of computer codes using unstructured meshes and running on parallel computing platforms
NREL	National Renewable Energy Laboratory
Pa	Pascal
psia	pounds per square inch absolute
psig	pounds per square inch gage
SINDA	SINDA/FLUINT is a comprehensive finite-difference, lumped parameter (circuit or network analogy) tool for heat transfer design analysis and fluid flow analysis in complex systems